

# New approach to image amplification based on an optically-pumped multi-core optical fiber

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## ABSTRACT

This paper describes a new approach to amplify optical images by using optically pumped doped cores in a multi-core optical fiber structure. This approach combines the high gain and high efficiency properties of cladding pumped optical amplifiers with the imaging properties of coherent fiber bundles. The individual cores correspond to the pixels in the image amplifier. We have demonstrated 3x3 arrays in an ytterbium-doped phosphate fiber energized by one multimode semiconductor diode. Each pixel is capable of high gain ( $> 20$  dB), low noise, and large acceptance angle ( $> 12$  degrees). We expect our glass and preform fabrication method to scale to over 100 pixels. The amplified image can preserve coherence (phase and wavelength) - or scramble the coherence depending on the design of the cores. This image amplifier is an enabling technology for any type of imaging system that is photon-starved and requires a compact and low noise image amplifier.

**Keywords:** image amplifier, fiber optic imaging, optical amplifier arrays, fiber optic amplifier, image intensifier, optical image processing, ytterbium doped amplifier, optical power amplifier, laser tracking and pointing

## 1. INTRODUCTION

The low noise amplification of weak light images is an important technology focus relevant in many application areas from optical metrology to optical signal processing. For example, laser tracking and pointing of remote targets for space/air surveillance and control applications requires low noise image amplifiers covering a wide field of view to improve signal to noise in image detection. Image amplifiers that preserve the optical phase are particularly useful in interferometric or coherent imaging applications. In acquisition, tracking, and pointing (ATP) systems, return images from single or multiple targets in a scene are usually very weak – and require sensitive focal plane array detectors with potentially long integration times. Figure 1 shows a typical system configuration for an ATP system. Return images are susceptible to a variety of disturbances from the atmosphere such as scintillations, beam wandering, clouds, and rain – which affect the strength and stability of the image. The detector must efficiently collect and render a 2-dimensional representation of the return image with high fidelity and high speed. A suitable image amplifier covering a wide field of view improves the overall signal to noise of the image detection process, leading to higher system performance – such as a longer target range capability or a stronger immunity to atmospheric disturbance. In this regard, compact, high electrical plug-in efficiency, and high gain optical amplifiers are particularly needed.

This paper focuses on the development of compact, high gain panoramic optical amplifiers suitable for image amplification. Our approach centers on a phosphate glass and fiber technology that enables much higher ytterbium doping than previously possible – resulting in high gain per unit length (5 dB/cm) and short fiber lengths (~5-10 cm). [2,3] This is combined with a pre-form and fiber drawing technology that makes possible the fabrication of two-dimensional arrays of doped cores embedded in a pump cladding layer – where each core represents a pixel in the image amplifier. The array structure is fabricated in a manner similar to optical fibers – tremendously significant in terms of realizing low cost devices. In addition, multimode semiconductor pump lasers simultaneously energize the entire image amplifying array - resulting in a massive, scalable, and highly cost-effective sharing of pump power. [4]

The approach described here combines the high gain and high efficiency properties of cladding pumped optical amplifiers with the imaging properties of coherent fiber bundles. In this demonstration, we produce a 3x3 active array arranged in a two-dimensional square pattern with each pixel capable of high gain ( $> 16$  dB), low noise, and large acceptance angle ( $> 12$  degrees). [5] The image amplifier is energized with 975 nm multimode laser diodes.

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In the past few years, telecommunication systems have driven rapid advances in the performance of high power optical amplifiers using cladding pumped rare-earth doped optical fibers. This technique makes efficient use of multimode pump diode power to energize a doped single mode core. Optical signals coupled into the central single mode core are amplified as they propagate. Silica-based ytterbium-doped double clad fibers have achieved over 100W power when pumped with multimode diode lasers. Clad pumping overcomes the problem of coupling high power pump light into a conventional single-clad single mode fiber. These devices are capable of amplifying light that is coupled into one single mode core – *but they are not meant to amplify an image*. Images contain many spatial frequencies, which cannot be coupled into a single mode core. Moreover, an image amplifier must preserve the spatial intensity distribution of the input – by making an appropriate mapping to the output image plane. It is clear that one single mode fiber is not capable of amplifying an image.

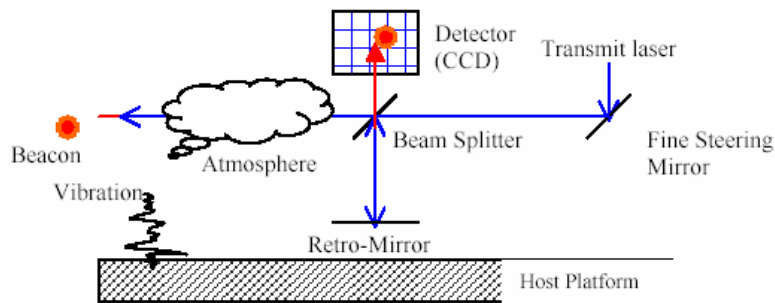


Fig. 1. Typical optical communications acquisition, tracking, and pointing system. [1]

Coherent fiber bundles are used to transfer and/or magnify optical images. Typically, a high density of fiber cores collects the light from the input facet, and transfers light energy along the fiber bundle to the output facet end. If the packing density is high enough and the propagation loss of the fibers is low enough, the image is reconstructed at the output facet of the bundle. Such coherent fiber bundles typically contain multimode glass cores with numerical apertures covering a wide range of values (0.20 – 0.35), serving to collect light over a wide range of acceptance angles. The number of core elements can reach thousands or more – with higher numbers corresponding to higher image resolution. Of course, since fiber bundles are made from passive optical fibers with no optical gain, they will lose optical power in the image transfer from input facet to output facet.

In our approach to image amplifying, we combine the high gain and high efficiency properties of cladding pumped optical amplifiers with the imaging properties of coherent fiber bundles.

There are several notable features of this approach to image amplification:

- The active core elements can be fabricated in glass fiber with a particular diameter ( $\sim 6\mu\text{m}$ ) and numerical aperture (NA). The NA governs the capture angle of the input light and can typically be between 0.06 and 0.30 - corresponding to an acceptance angle of between 3.4 degrees and 17.5 degrees;
- Low noise figure ( $< 5\text{ dB}$ ) and large optical gain ( $> 20\text{ dB}$ ) for each core (i.e. pixel) in a two dimensional array;
- High Yb-doping in cores enables high gain in a short length of fiber ( $< 10\text{ cm}$ );
- Core fill factor for image amplifying fiber is greater than 30%;
- Core separation can be designed to completely suppress core-core optical coupling or, alternatively, to allow for optical cross coupling;
- The phase of the amplified image can be preserved using single mode active cores (coherent amplification) or scrambled using multimode cores (incoherent amplification);
- Effective thermal management in optical fiber geometry relieves thermal distortions in image amplifier;

- Device is energized with commercially available semiconductor multimode pump diodes just as in single core high power fiber amplifiers;

## 2. GLASS AND FIBER

Figure 2 shows a cross-sectional image of the cleaved surface of the 3x3 amplifier array. The 9-core array structure consists of Yb-doped (6% by weight) cores with 6  $\mu\text{m}$  diameter and numerical aperture of 0.20 embedded in an inner clad with numerical aperture of 0.20. Each doped core has an acceptance angle of nearly 12 degrees. The diameter of the first cladding layer is 70  $\mu\text{m}$ , and the outer clad diameter is 120  $\mu\text{m}$ . The center-center spacing between the central core and those nearest the center is 14  $\mu\text{m}$  and those cores furthest away are 20  $\mu\text{m}$ . The core fill factor is greater than 30%. The multi-core array structure is produced in a method analogous to usual optical fiber drawing for a single core. We take a cladding glass pre-form and mechanically drill 9 cylindrical holes. Core glass is machined into rods and placed in cylindrical pre-forms made of the same cladding glass. The 9 core sections are placed in the 9 holes, and the entire structure is pulled much like typical single core optical fibers. This fabrication method offers tremendous flexibility in design and contrasts sharply with the more standard chemical vapor deposition method of pre-form fabrication in usual silica fibers. In addition, the optical fiber-drawing method is by its nature a low cost, highly scalable, and highly reproducible manufacturing approach. Although here we show structure with 9 active pixels, we expect no difficulty to scale up the number of pixels to reach over 100.

The separation between the cores was chosen such that no optical cross coupling with adjacent cores would occur. Within the range of practical NA (0.06 to 0.30), the amplifying core can be either single mode (for phase preserving amplification) or multimode (for incoherent amplification). The active core elements are easily formed with a circular cross section – which is desirable to preserve polarization-independent device operation. The output image from this device is a 1:1 mapping of the input image. The amplifying multi-core fiber captures images (or point targets) in its array of active cores and transfers an amplified version to downstream detection.

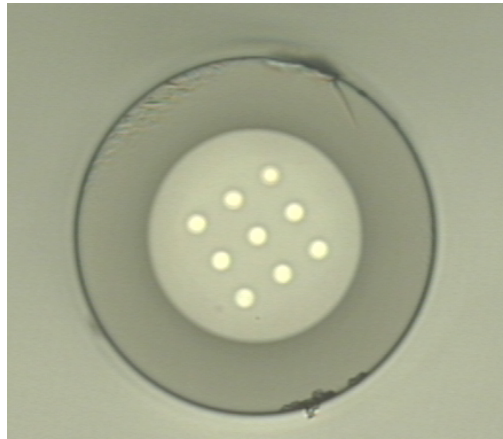


Fig. 2. Cross sectional view of a multi-core cladding pumped image amplifying fiber. The doped cores are arranged in a two-dimensional array. The inner cladding region with diameter of 70  $\mu\text{m}$  contains active cores and confines pump light. The fiber diameter is 120  $\mu\text{m}$ .

## 3. EXPERIMENTAL APPROACH

To characterize the image amplifying fiber, we tested the optical gain achievable from the active cores, or pixels. This is done by fusion splicing a commercial 1060 single mode fiber (SMF) onto the amplifying fiber such that the core of SMF is connected to the central core of image fiber. With this characterization approach, we can avoid the difficulties of free space optical coupling of light into the pixels – and ensure low loss coupling of signal power into the amplifying

cores. Passive 1060 single mode fiber was attached on either end of various lengths of image amplifying fiber ranging from 3 cm to 10 cm. A single mode semiconductor pump diode at 975nm was used to energize the active core. In the case of single mode pumping, only one core is active; however, this is useful to characterize the gain characteristics of a doped core. In conjunction with a fiber based wavelength division multiplexer (WDM), pump and signal light were injected into the central core of the array. Narrow band ( $< 0.15$  nm) optical signals were produced by reflecting a broadband optical source from narrow band reflecting fiber bragg gratings. Signal gain was detected using an optical spectrum analyzer. Alternatively, to simultaneously energize the entire array, light from a multimode semiconductor pump diode at 975 nm was injected into the inner cladding via a double clad passive fiber.

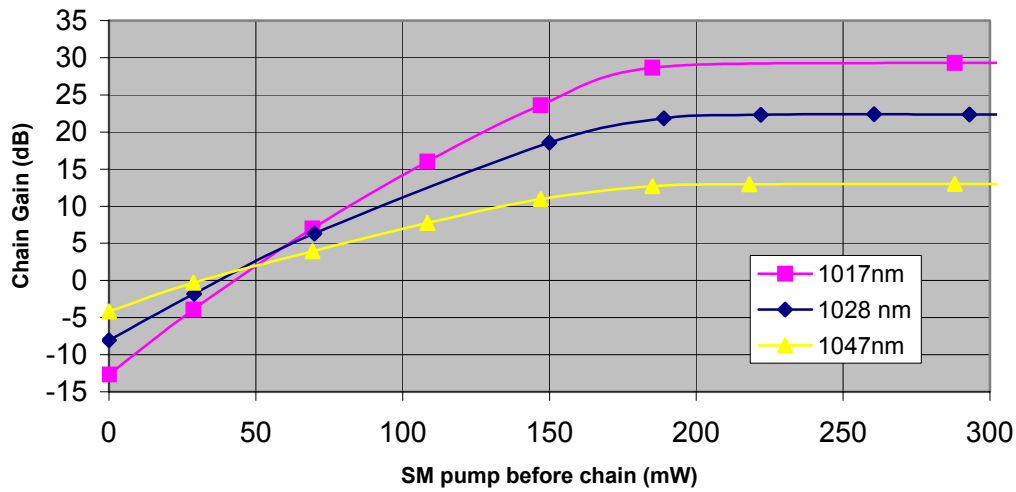


Fig. 3. Gain of central core of image amplifying fiber pumped as function of single mode pump power measured at 3 different signal wavelengths. Image fiber is 6 cm long.

#### 4. IMAGE AMPLIFIER CHARACTERIZATION

Figure 3 shows the measured net gain going through the central core of a 6 cm long image amplifying fiber for various input wavelengths as a function of single mode pump power. At 1017 nm, the gain per unit length is approximately 5 dB/cm and the total gain approaches 30 dB. The gain does not increase for pump power above 200 mW because the inversion rate reaches a maximum and saturates. This experiment shows how much optical gain is available when the core is sufficiently pumped. For energizing many cores simultaneously, multimode pumping is preferred. In this case, multimode pump power is deposited in all the cores although we measure only the central core. A pump power of 1.8 W produces 17 dB optical gain in the central core at 1017 nm signal wavelength in a 6 cm length of amplifying fiber. To obtain the same gain in the single mode pumping case, approximately 110 mW of pump power is needed. We detected that 40% of the multimode pump power exits the output fiber and estimate that 10% is lost or scattered. This leaves 50% absorbed over 9 cores over the 6 cm of fiber length, or 5.5% per core. In other words, 5.5% of 1.8 W ( $\sim 100$  mW) is absorbed in each core. Interestingly, this is roughly consistent with the single mode result of 110 mW. In spite of the multimode pump's inhomogeneous spatial distribution, it uniformly energizes an array of cores. Simulation results indicate that the maximum gain deviation across the entire array is less than 1 dB. Simulations also indicate that there is a trade-off between improved uniformity across the array and pump power. Using more pump power can drive the pixels into saturation – producing a more uniform gain performance.

Figure 4 shows the residual pump beam and the amplified spontaneous emission at the output side of the fiber. The pump power is confined into the inner cladding of the fiber. The active cores show no pump power since it is completely absorbed in those regions. Using a spectral filter to remove any residual pump power, the image of the amplified spontaneous emission (ASE) ( $\lambda > 1020$  nm) from the active pixels shows that all 9 cores are nearly uniformly

energized, and that all the ASE is captured in the amplifying cores. This is a strong indication that if signals were injected into all 9 cores simultaneously that the gain per pixel would be nearly the same.

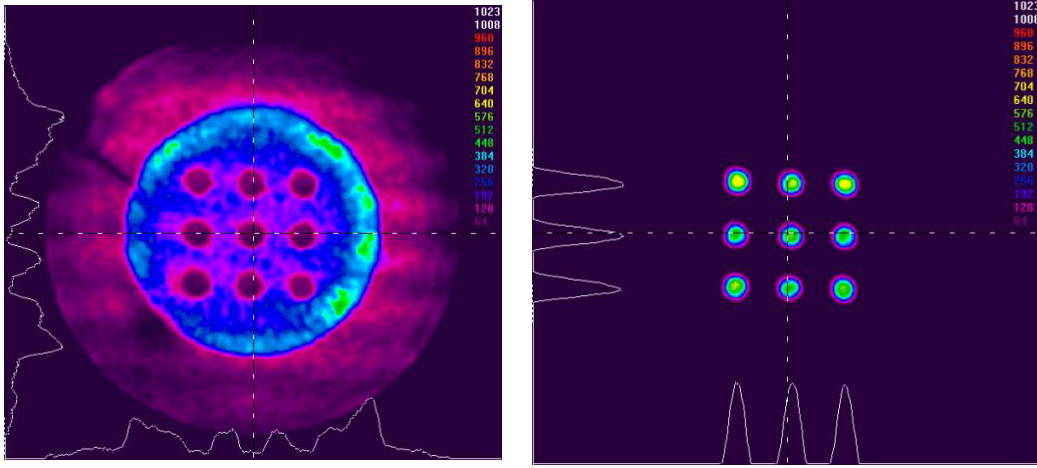


Fig. 4. Image of output facet of image amplifying fiber. Left, image at pump wavelength of 975 nm showing multi-mode pump power confined in inner cladding and active cores depleted of pump power. Right, amplified spontaneous emission (ASE) from active cores ( $\lambda > 1020$  nm) showing uniformity of ASE emission from all 9 active elements.

To demonstrate and characterize image amplification in this image amplifying fiber, we fusion spliced a multimode step index optical fiber to the image amplifying fiber. This technique has several purposes. One it allows for convenient coupling of signal and pump power in an all-fiber format. Second, it minimizes reflections that would occur between the facet of the image amplifying fiber and the air. In actual applications, the facet of the image amplifying fiber would be treated with a cleaved angle and/or anti-reflection coating so as to minimize reflections at the interfaces with free space beams.

The input signal light was derived from an ASE source covering a wavelength range from 1000 nm to 1060 nm with power concentrated in a 20 nm bandwidth centered at 1020 nm. The single mode ASE source was coupled into a step index multimode fiber – such that the input signal light was scrambled across the entire core region of the multimode fiber. The integrated signal power is 0.7 mW across a 90  $\mu\text{m}$  diameter of the inner clad of the multimode fiber. Pump light at 975nm was coupled into the same fiber via a coupler such that both pump and signal were confined to the 90 $\mu\text{m}$  inner clad region. The multimode fiber was then fusion spliced to the 3x3 image amplifying fiber. The image amplifying pixel array captures signal light into the 9 pixels and amplifies the signal when pump light is applied. For a fiber length of only 8cm and optical pump power of 1.3 W, each pixel produces more than 16 dB of optical signal gain. Figure 5 shows a three-dimensional representation of the amplified signals from the array. The input signal light is uniformly illuminating the amplifier array – and the resulting signals are correspondingly uniform in gain response.

## 5. MODELING APPROACH AND RESULTS

A suite of modeling tools for the design and assessment of cladding-pumped Er/Yb and Yb fiber amplifiers has been developed, [6] and adapted to analyze the performance and design of multi-core image arrays. This was motivated by the deficiencies encountered by using standard beam propagation methods (BPM) that are normally used to describe wave propagation in optical structures. Although standard BPM reflects the changes in mode profile caused by the elevated absorption coefficient and thereby incorporates the absorptive mode coupling effect, BPM does not account for the detailed nonlinear saturation behavior of the absorption coefficient, which becomes significant at the highly elevated doping levels achieved in these fibers.

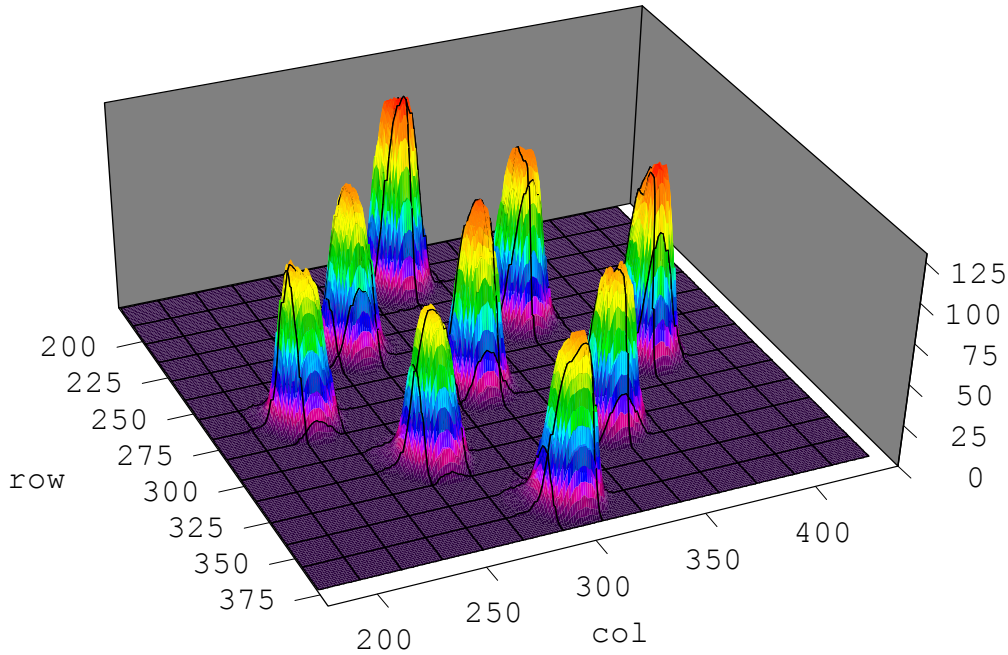


Fig. 5. A three-dimensional representation of the amplified signals from the image amplifying fiber. The pixels are confined within a cladding diameter of  $70\text{ }\mu\text{m}$ . The center-center spacing between the central core and those nearest the center is  $14\text{ }\mu\text{m}$  and those cores furthest away are  $20\text{ }\mu\text{m}$ . The scales on the figure are for illustrative purposes. A broadband incoherent source centered at  $1020\text{nm}$  illuminates the  $3\times 3$  array and produces more than  $16\text{ dB}$  optical gain per pixel when optically pumped with  $1.3\text{W}$ . The fiber length is  $8\text{ cm}$ .

The multi-mode nature of cladding pumped schemes and the strong nonlinearities in highly Er/Yb-doped fiber amplifiers requires a new modeling method, which can effectively deal with these difficult issues. Our new modeling method, called the Effective BPM, combines BPM for the fields and rate equations for the laser medium. In our method, the nonlinear rate equations are solved numerically giving an accurate pump absorption coefficient for BPM. The profile of the pumping field obtained by BPM is then used to determine all the characteristics of each amplifying core, such as gain, noise figure, output power, etc... The model can handle multiple cores placed at arbitrary locations, and arbitrary pump cladding shape. We find that this theoretical approach gives good agreement with experimental data from multi-mode pumped multi-core arrays.

Figure 6 shows the simulated gain spectrum for various lengths under  $1.8\text{W}$  of multimode pumping. Peak gain occurs near  $1020\text{ nm}$  with a  $3\text{ dB}$  bandwidth that exceeds  $20\text{ nm}$ . Gain greater than  $20\text{ dB}$  is achievable with a  $10\text{cm}$  long image amplifying fiber. This indicates that the image amplifier can achieve high gain both in single wavelength operation and for a band of signal wavelengths. The model allows for the important estimate of noise figure. Under the same pump conditions as in Fig. 6, the noise figure is less than  $5.5\text{ dB}$  for wavelengths from  $1020\text{nm}$  and longer. Also important is that if the pump wavelength is changed from  $975\text{nm}$  to  $910\text{ nm}$ , the noise figure can be reduced and is less than  $5\text{ dB}$ .



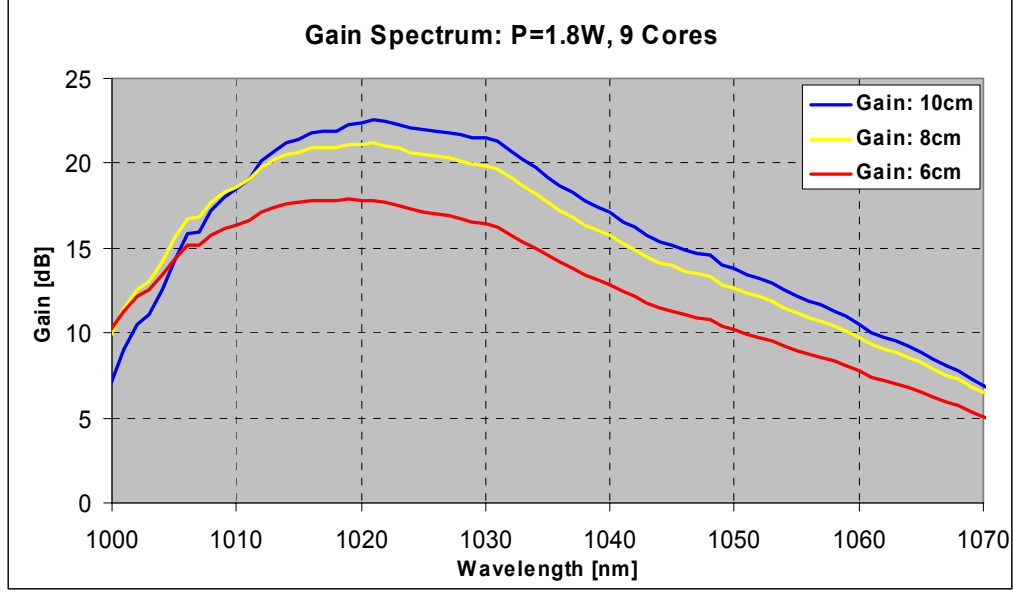


Fig. 6. Simulated gain spectrum for 9-core imaging fibers having different lengths with multimode pumping (1.8 W) co-propagating with signal.

## 6. SUMMARY

In this paper we describe a new approach to amplify optical images by using optically pumped doped cores in a multi-core optical fiber structure. This image amplifying fiber approach combines the high gain and high efficiency properties of cladding pumped optical amplifiers with the imaging properties of coherent fiber bundles. The individual cores correspond to the pixels in the image amplifier. We have characterized the performance of a 3x3 array fabricated in an ytterbium-doped phosphate fiber energized by one multimode semiconductor diode. Depending on the pump power and fiber length, it is possible to obtain high gain ( $> 20$  dB) over a wavelength band centered at  $\sim 1020$  nm. The pixel elements have a wide field of view (12 degrees), determined by the choice of active core numerical aperture. We expect that this general fabrication and multimode pumping method will scale to over a hundred pixel elements in a single image amplifying fiber. The amplified image can preserve coherence (phase and wavelength) - or scramble the coherence depending on the design of the cores. This image amplifier is an enabling technology for any type of imaging system that is photon-starved and requires a compact and low noise image amplifier. It will be particularly useful for laser tracking and pointing of remote targets in space/air surveillance and control applications where low noise image amplifiers covering a wide field of view can dramatically improve the signal to noise in image detection.

## 7. ACKNOWLEDGEMENTS

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